

Attorney Docket No. RTN-177PUS

**EFFICIENT TECHNIQUE FOR ESTIMATING ELEVATION ANGLE WHEN  
USING A BROAD BEAM FOR SEARCH IN A RADAR.**

**BACKGROUND**

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5           The invention relates generally to radar systems.

In ground-based search radar systems with rotating (360°) antennas, a broad fan beam or shaped beam, e.g., a cosecant-squared beam, can be used to efficiently search over large elevation angles. This type of approach to searching for a target over a large angular search area is less time consuming than a single sequential beam approach. Typically, an elevation  
10       monopulse channel and an azimuth monopulse channel provide an accurate estimate of elevation angle and azimuth angle, respectively, for a target detected by narrow pencil beams. Unfortunately, accurate elevation estimates cannot be obtained for a target detected by the broad beam. One solution to this problem is to use a stacked beam on receive. The use of a stacked beam is costly, however, as it requires one or two receivers for each beam in the stacked beam.

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**SUMMARY**

The present invention is therefore directed towards a mechanism for efficiently determining elevation angle information of a target detected in elevation with a broad beam such as a cosecant-squared beam.

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In one aspect, therefore, the present invention provides methods and apparatus for determining target elevation during a radar search. The methods include determining the range of any target detected during a search with a broad beam covering a broad angular search area and, based on the determined range, transmitting consecutive beams at increasing search elevation angles in the broad angular search area and using echo signals of the consecutive  
25       beams to obtain an elevation angle estimate for the target.

Embodiments of the invention may include one or more of the following features.

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The broad beam can be a shaped cosecant-squared beam.

The consecutive beams can be transmitted sequentially in time.

The first of the consecutive beams (the one at the lowest elevation angle) can be focused.

Alternatively, it can be slightly defocused. The succeeding beams at successively higher elevation angles can be defocused by spoiling factors that increase with the increasing search angles. Typically all but the first one of the consecutive beams is defocused.

For a pulse Doppler radar, the transmission of the consecutive beams can include transmitting a pulse Doppler waveform which includes a set of transmit bursts, each transmit burst including a number of sub-pulses. Consecutive groups of subpulses in each transmit burst correspond to the consecutive beams. Corresponding numbered sub-pulses in each of the transmit bursts of the set have the same carrier frequency. The sub-pulses in each transmit burst can have different carrier frequencies. It is, however, possible although not generally preferred, to have the same carrier frequencies for different groups (or bursts) of sub-pulses.

Using the echo signals includes processing echo signals of the first one of the consecutive beams to detect the target. If the target is detected, an elevation angle estimate for the target is determined. Using the echo signals further includes (i) processing, in turn, echo signals of the defocused consecutive beams in the sum and difference channels until the target is detected in one of the defocused consecutive beams; (ii) using the results of the processing of the echo signals of the one of the defocused consecutive beams in which the target is detected to provide a first estimate of the elevation angle of the target; (iii) transmitting a focused beam towards the target based on the first estimate; and (iv) processing echo signals of the focused beam in the sum and difference channels to detect the target and determine a second, more accurate estimate of the elevation angle of the target.

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Particular implementations of the invention may provide one or more of the following advantages. The search mechanism is quite efficient in that it makes use of the knowledge of the range of the target and the radar system's elevation scan capability together with a time multiplexed waveform to obtain a more accurate determination of the target elevation. The time multiplexed waveform transmits pulses at different elevation angles to look for the target during one dwell time. These pulses use defocused beams. The defocusing is increased with the degree of the elevation angle being searched. Such defocusing is possible and desirable because the range to the detected target decreases with increasing elevation angle. The defocusing is needed in order to efficiently cover the elevation uncertainty angle which one has after detecting the target with the cosecant-squared beam or the fan beam. Once the target is located with the defocused beam, a focused beam is used to get the final, highly accurate elevation angle estimate. With an antenna having an azimuth look-back capability, it is possible to do the dwells with the defocused and focused beams during the same rotation period as that in which the target is detected. Thus, the approach of the present invention provides for efficient searching above a certain low elevation angle, e.g., six degrees (or even zero degrees), without adversely impacting search frame time as with the conventional single sequential beam approach.

Other features and advantages of the invention will be apparent from the following detailed description and from the claims.

**DESCRIPTION OF DRAWINGS**

FIG. 1 is a block diagram of a pulse Doppler monopulse radar system.

FIG. 2 is depiction of transmit and receive beams used by the monopulse radar system of

FIG. 1 for search coverage from 0 to 70 degrees.

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FIG. 3 is a flow diagram of the operational flow of a broad beam target search that uses an elevation angle determination process for determining elevation angles for targets detected in higher elevation.

FIG. 4 is a flow diagram of the elevation angle determination process (of FIG. 3) for a  
5 single detected target.

FIG. 5 is an illustration of the waveform used during the elevation angle determination process from FIG. 4.

FIG. 6 is a detailed block diagram of the detector block of FIG. 1.

FIG. 7 is a flow diagram of the elevation angle determination process for multiple  
10 detected targets.

Like reference numerals will be used to represent like elements.

**DETAILED DESCRIPTION**

Referring to FIG. 1, a radar system 10 is shown. The radar system 10 may be a ground-  
15 based radar system, but could be used on a ship, aircraft or spacecraft as well. The radar system 10 includes a transmitter 12, the output of which is delivered to an antenna 14 (in an antenna system 16) for radiation in the form of a transmit beam. The antenna 14 collects echo signals received from a target and a combiner 18 (also in the antenna system 16) combines the echo signals into receive signals 20, which are processed by a receiver 22 to detect the presence of the  
20 target and determine its location in range and in angle. In the illustrated embodiment, the antenna 14 is a mechanically rotating antenna to scan in azimuth. However, the antenna 14 could also be an electronically scanned in azimuth antenna. A duplexer 24 coupled to the transmitter 12, receiver 22 and antenna 14 allows the antenna 14 to be used on a time-shared basis for both transmitting and receiving.

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Still referring to FIG. 1, the receiver 22 includes a receiver block 30 to perform RF-to-IF conversion, amplification, A/D conversion, possibly pulse compression filtering, as well as includes a detector block 32 and a monopulse processing block 34. The detector block 32 detects the presence of the target. More specifically, the detector block 32 performs Discrete  
5 Fourier Transforms (DFTs), envelope detection and post-detection integration (video integration), among other functions. The monopulse processing block 34 produces angle information 35 from the output of the detector block 32. The angle information includes information indicative of estimated elevation angle and azimuth angle.

In the illustrated embodiment, the receiver 22 is a monopulse receiver. Thus, receive  
10 signals 20 include three signals, a sum (S) signal 36, an elevation difference ("ΔEL") signal 38 and an azimuth difference ("ΔAZ") signal 40. The receiver block 30 and the detector block 32 can be partitioned into three separate channels, one for each of the signals 36, 38 and 40, respectively. Thus, receiver block 30 includes receiver blocks 48, 50 and 52, and detector block 32 includes detector blocks 54, 56 and 58. The receiver block 48 and detector block 54 form a  
15 sum channel to process the sum signal 36. The receiver block 50 and detector block 56 form an elevation difference channel to process the elevation difference signal 38. The receiver block 52 and the detector block 58 forms an azimuth difference channel to process the azimuth difference signal 40.

The sum channel is further coupled to a threshold detect unit 60, which generates a range  
20 signal from the output of the sum channel's detector block 54. The receiver 22 also includes a detection verification block 62 as well as a range and Doppler ambiguity removal block 64. Although not shown, the receiver 22 may be coupled to a tracker.

The output of the monopulse processing block 34 is connected to a controller/interface  
68. The controller 68 provides control signals 70 to functional blocks of the system 10. In

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particular, the controller 68 enables the system 10 to perform a target search at higher elevation using a broad search beam, and to determine an accurate elevation angle estimation of a target detected by such a broad search beam, as will be described.

A "broad" elevation search beam, that is, a beam that covers a broad elevation angular search area, is a defocused (or spoiled) beam that is at least as wide as the combined beamwidths of two focused beams. Typically, however, it is much wider. A "focused" beam is a beam that has no phase modulation (for the illumination across the antenna) in the vertical direction, resulting in a beamwidth in elevation of approximately  $\lambda/H$ , where H is the height of the antenna. In contrast, a "defocused" beam is a beam that has phase modulation in the vertical direction. For example, a defocused beam could have a quadratic-like phase modulation.

Those aspects of the radar system 10 not described herein can be implemented according to known radar techniques, for example, those found in the "Aspects of Modern Radar," edited by Eli Brookner, (Artech House, Inc., 1988), incorporated herein by reference, and other sources. For example, monopulse techniques are discussed at some length in Chapter 5, pages 297-335, of the above-referenced Brookner text.

During a target search, the antenna 14 transmits one of two different types of beams depending on search elevation. Referring to FIG. 2, exemplary search coverage 80 includes on transmit two narrow beams 82 ("beam 1") and 84 ("beam 2") and a broad search beam 86 ("beam 3"). The narrow beams 82, 84 are used for searching at low elevation angle (e.g., from the horizon up to  $5.6^\circ$  in elevation, as shown) at long range. For an efficient higher elevation search, for example, when searching elevation angles from  $5.6^\circ$  up to  $70^\circ$ , the broad beam 86 is used. The broad beam 86 can be a beam such as a cosecant-squared (" $\text{CSC}^2$ ") shaped beam (as illustrated), which is a recognized beam pattern for searching large angular volume. The lower beams 82 and 84 use all three channels, in particular, the sum channel to detect the target and

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elevation and azimuth monopulse receive channels to provide estimates of the target azimuth ("AZ") and elevation ("EL") angles. The broad beam 86, e.g., the CSC<sup>2</sup> beam, does not use AZ or EL monopulse. Therefore, the broad beam 86 does not provide any EL angle estimates. Consequently, the beam 86 obtains good elevation coverage at the sacrifice of elevation angle measurement accuracy. Furthermore, it has the important advantage of providing the large angle coverage with only three receivers, thus lowering cost. Finally, the broad beam provides such large angular coverage in a short time, thus allowing a fast volume revisit time.

In one embodiment, when illuminating the search volume with the broad beam, the two channels ordinarily used on receive for the AZ and EL monopulse with beams 1 and 2 are also used for focused receive beams 88 and 90 ("beam 3A" and "beam 3B") to provide better long range coverage in a lower elevation search area of the broad beam 86, for example, in the illustrated embodiment, between the angles 5.6° and 11.2°. They also provide some elevation angle estimation, specifically, if the target is detected in either of these focused receive beams 88 and 90, an initial rough estimate of its elevation angle is available. The amplitude of the returns in the two receiver channels associated with these two beams give some indication of the target's location in elevation. That is, elevation amplitude monopulse estimates can be obtained from the outputs of beams 88 and 90. When such an estimate is available, the system 10 transmits a focused beam in the direction of the target's location. This focused transmit beam has monopulse AZ and EL, and provides an accurate estimate of the target's EL and AZ angles. A pulse Doppler waveform whose pulse repetition frequency ("PRF") has no range and Doppler eclipsing could be used for the focused transmit beam. If it is determined that the target is not detected by beams 3A or 3B (which provide coverage between angles 5.6° and 11.2°), the system 10 uses a special elevation angle estimation process involving additional transmit beams, including beam 92 (beam 1C), beam 94 (beam 2C), beam 96 (beam 3C), beam 98 (beam 4C) and

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beam 99 (beam 5C), at increasing search elevation angles, as will be described below with reference to FIGS. 3-7.

Referring to FIG. 3, an overview of a broad beam search process 100 that uses an elevation angle determination process for determining elevation angles for targets detected at the higher elevation angles covered by beam 86 is shown. The process 100 is performed by system 10 under the control of the controller 68. To begin, the system 10 transmits a broad beam to search for the target in elevation (step 101). In the illustrated embodiment, and as was indicated earlier, the broad beam 86 is a shaped beam, more specifically, a CSC<sup>2</sup> beam. In one embodiment a PRF pulse Doppler waveform having range and/or Doppler ambiguities is used. The system 10 detects and determines the range of a target in the broad angular elevation search area covered by the broad beam. Optionally, the system 10 uses the elevation and azimuth difference channels to form receive beams (beams 3A and 3B) to determine if the target is detected in one of those receive beams (step 102). During detection, the system uses a low false alarm probability (Pfa) setting like 10<sup>-6</sup>. Upon detection, the system 10 verifies that the detection is an actual echo from a real target rather than a false alarm (step 104). The verify is done using a larger Pfa of, say, 10<sup>-2</sup>. This is possible as there are fewer range-Doppler cells in which to look for the target during verification. If system 10 has an azimuth scan it can look back for the verification. Alternately, the verification can be performed on the next scan (rotation). Nominally the verification would be performed with a pulse Doppler waveform having the same carrier frequency and PRF as was used in the detection of the target to allow verification of the target with minimum radar energy.

If the detection verification confirms that a target is present, one or more additional pulse Doppler bursts having the same carrier frequency at different PRFs are used to remove the range-Doppler ambiguities (step 106). This removal can be done with further look backs or can occur

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10 transmits sequentially in time the focused beam 1C (or alternatively, a defocused beam 1C) and defocused beams 2C through 5C, and, for each of these beams, uses the sum, ΔEL and ΔAZ channels to obtain an estimate of the target elevation and azimuth angles (step 126). If the target is detected in one of beams 2C through 5C, the system 10 points a focused beam in the direction

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1. A method for determining target elevation during a radar search comprising:  
determining the range of any target detected during a search with a broad beam covering  
a broad angular search area;  
based on the determined range, transmitting consecutive beams at increasing search  
5 elevation angles in the broad angular search area; and  
using echo signals of the consecutive beams to determine an elevation angle estimate for  
the target.
2. The method of claim 1 wherein the broad beam comprises a shaped cosecant-squared  
10 beam.
3. The method of claim 1 wherein one of the consecutive beams is a focused beam.
4. The method of claim 1 wherein all but a first one of the consecutive beams are defocused  
beams.
- 15 5. The method of claim 4 wherein the defocused ones of the consecutive beams are  
defocused by spoiling factors that increase with the increasing elevation search angles.
6. The method of claim 1 wherein transmitting comprises:  
transmitting a time-multiplexed pulse Doppler waveform which includes a set of transmit  
bursts, each transmit burst including a number of sub-pulses.

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7. The method of claim 6 wherein consecutive groups of sub-pulses in each transmit burst correspond to the consecutive beams.

8. The method of claim 7 wherein corresponding ones of the sub-pulses in each of the transmit bursts of the set have the same carrier frequency and are coherent with each other.

9. The method of claim 8 wherein the different sub-pulses of each transmit burst have different carrier frequencies.

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10. The method of claim 8 wherein the sub-pulses of each group of each transmit burst have different frequencies and corresponding ones of the sub-pulses in different groups for different beams can have the same carrier frequency.

10 11. The method of claim 9 wherein all but a first one of the consecutive beams are defocused.

12. The method of claim 9 wherein all of the consecutive beams are defocused beams.

13. The method of claim 4 wherein using echo signals comprises:

15 processing echo signals of the first one of the consecutive beams to detect the target; and  
if the target is detected, using results of the processing to determine an elevation angle estimate for the target.

14. - The method of claim 13 wherein using echo signals further comprises:

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processing, in turn, echo signals of the defocused consecutive beams in sum and difference channels until the target is detected in one of the defocused consecutive beams;

using the results of the processing of the echo signals of the one of the defocused consecutive beams in which the target is detected to provide a first estimate of the elevation

5 angle of the target;

transmitting a focused beam towards the target based on the first estimate; and

processing echo signals of the focused beam in the sum and difference channels to detect the target and determine a second, more accurate estimate of the elevation angle of the target.

10 15. The method of claim 14 further comprising:

using receive beams received by available elevation and azimuth difference channels for a lower elevation search area covered by the broad beam at an elevation angle below that at which the consecutive beams are transmitted and prior to the transmission of the consecutive beams, to determine whether any targets are detected in the lower elevation search area; and

15 if multiple targets are detected and at least one of the multiple targets is detected in the lower elevation search area as a lower elevation target, then performing the steps of:

obtaining a rough elevation angle estimate for the lower elevation target; and

transmitting a focused beam towards the lower elevation target based in the rough estimate.

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16. The method of claim 15 wherein transmitting the focused beam towards the lower elevation target based on the rough estimate occurs in a single time-multiplexed pulse Doppler waveform.

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17. The method of claim 15 further comprising:

if multiple targets are detected and all of the multiple targets are detected in the broad angular search area above the lower elevation search area, then performing the steps of:

5       processing, in turn, echo signals of the defocused consecutive beams in sum and difference channels until either all of the multiple targets are detected or all of the echo signals of the defocused consecutive beams have been processed;

if all of the multiple targets are not detected with one pulse repetition frequency (PRF), then repeating the steps of transmitting consecutive beams with a different PRF and processing  
10       the echo signals of each consecutive beam until all of the multiple targets are detected;

using the results of the processing steps to provide first estimates of the elevation angle of each target;

transmitting a focused beam towards each target based on the first estimate of such target;  
and

15       processing echo signals of the focused beams in the sum and difference channels to detect each target and determine a second, more accurate estimate of the elevation angle of each target.

18. The method of claim 17 wherein transmitting the focused beam towards each target occurs in a single time-multiplexed pulse Doppler waveform.

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19. The method of claim 1 wherein transmitting comprises:

transmitting a time-multiplexed pulse Doppler waveform which includes a set of transmit bursts, each transmit burst including the same number of sub-pulses.

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20. The method of claim 1 wherein transmitting comprises:  
transmitting a waveform comprising a single transmit burst.

5 21. The method of claim 20 wherein consecutive groups of sub-pulses in the transmit burst correspond to the consecutive beams.

22. The method of claim 21 wherein corresponding ones of the sub-pulses in each of the transmit burst of the set have the same carrier frequency and are coherent with each other.

23. The method of claim 22 wherein the different sub-pulses of the transmit burst have different carrier frequencies.

10 24. The method of claim 22 wherein the sub-pulses of each group of the transmit burst have different frequencies and corresponding ones of the sub-pulses in different groups for different beams can have the same carrier frequency.

15 25. The method of claim 23 wherein all but a first one of the consecutive beams are defocused.

26. The method of claim 23 wherein all of the consecutive beams are defocused beams.

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27. The method of claim 1 further comprising:

using one or more pencil beams to detect the target at elevation angles lower than those covered by the broad beam.

5 28. The method of claim 1 wherein transmitting comprises transmitting the consecutive beams sequentially in time.

29. A method for determining target location during a radar search comprising:

determining the range of any target detected during a search with a broad beam

10 covering a broad angular search area;

based on the determined range, transmitting consecutive beams at increasing search elevation angles in the broad angular search area; and

using echo signals of the consecutive beams to determine at least one angle estimate for the target.

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30. The method of claim 29 wherein the at least one angle estimate comprises an elevation angle estimate and an azimuth angle estimate.

31. A radar system comprising:

20 means for determining the range of any target detected during a search with a broad beam covering a broad angular search area;

means for transmitting consecutive beams at increasing search elevation angles in the broad angular search area for the determined range; and

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means for using echo signals of the consecutive beams to determine an elevation angle estimate for the target.

32. The radar system comprising:

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an antenna system;

a transmitter coupled to the antenna system;

a receiver coupled to the antenna system;

a controller to control the transmitter, receiver and antenna system;

wherein the receiver, responsive to control signals from the controller, operates to

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determine the range of any target detected during a search with a broad beam covering a broad angular search area;

wherein the transmitter, responsive to signals from the controller, operates to transmit, via the antenna system, consecutive beams at increasing search elevation angles in the broad angular search area for the determined range; and

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wherein the receiver, responsive to control signals from the controller, operates to use echo signals of the consecutive beams received via the antenna system to determine an elevation angle estimate for the target.

33. The radar system of claim 32 wherein the broad beam comprises a shaped cosecant-

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squared beam.

34. The radar system of claim 32 wherein at least one of the consecutive beams is a focused beam.

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35. The radar system of claim 32 wherein all but a first one of the consecutive beams are defocused beams.

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5 36. The radar system of claim 32 wherein all of the consecutive beams are defocused beams.

37. The radar system of claim 35 wherein the defocused ones of the consecutive beams are defocused by spoiling factors that increase with each consecutive beam.

10 36. The radar system of claim 32 wherein the transmitted consecutive beams are transmitted in a single time multiplexed pulse Doppler waveform which includes a set of transmit bursts, each burst including a number of sub-pulses with each sub-pulse forming a pulse Doppler waveform.

15 37. The radar system of claim 36 wherein consecutive groups of sub-pulses in each transmit burst correspond to the consecutive multiple beams.

38. The radar system of claim 37 wherein a corresponding ones of the sub-pulses in each of the transmit bursts of the set have the same carrier frequency and are coherent with each other.

39. The radar system of claim 37 wherein the sub-pulses of each transmit burst have different carrier frequencies.



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40. The radar system of claim 39 wherein the sub-pulses of each group of each transmit burst have different frequencies and corresponding ones of the sub-pulses in different groups for different beams can have the same carrier frequency.

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41. The radar system of claim 39 wherein all but a first one of the consecutive beams are defocused.

42. The radar system of claim 39 wherein all of the consecutive beams are defocused beams.

43. The radar system of claim 32 wherein the echo signals are used to process echo signals of the first one of the consecutive beams to detect the target and, if the target is detected, determine from the results of the processing an elevation angle estimate for the target.

44. The radar system of claim 43 wherein the echo signals are used to process, in turn, echo signals of the defocused consecutive beams in sum and difference channels until the target is detected in one of the defocused consecutive beams, obtain from the results of the processing of the echo signals of the one of the defocused consecutive beams in which the target is detected a first estimate of the elevation angle of the target, transmit a focused beam towards the target based on the first estimate and process echo signals of the focused beam in the sum and difference channels to detect the target and determine a second, more accurate estimate of the elevation angle of the target.

45. The radar system of claim 32 wherein the focused beam is transmitted as a time-

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multiplexed pulse Doppler waveform which includes a set of transmit bursts, each transmit burst including the same number of sub-pulses.

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46. The radar system of claim 32 wherein the focused beam is transmitted as a pulsed signal  
5 comprising a single transmit burst.

47. The radar system of claim 46 wherein consecutive groups of sub-pulses in the transmit burst correspond to the consecutive beams.

48. The radar system of claim 47 wherein corresponding ones of the sub-pulses in each of the transmit burst of the set have the same carrier frequency and are coherent with each other.

49. The radar system of claim 48 wherein the different sub-pulses of the transmit burst  
10 have different carrier frequencies.

50. The radar system of claim 48 wherein the sub-pulses of each group of the transmit burst have different frequencies and corresponding ones of the sub-pulses in different groups for different beams can have the same carrier frequency.

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51. The radar system of claim 49 wherein all but a first one of the consecutive beams are defocused.

52. The radar system of claim 49 wherein all of the consecutive beams are defocused

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beams.

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53. The radar system of claim 32 wherein one or more pencil beams are used to detect the target at elevation angles lower than those covered by the broad beam.

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54. A radar system for determining target location during a radar search comprising:

means for determining the range of any target detected during a search with a broad

beam covering a broad angular search area;

means for transmitting consecutive beams at increasing search elevation angles in the

10 broad angular search area based on the determined range; and

means for using echo signals of the consecutive beams to determine at least one angle estimate for the target.

55. The radar system of claim 54 wherein the at least one angle estimate comprises an

15 elevation angle estimate and an azimuth angle estimate.

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**MULTIPLE RADAR COMBINING FOR INCREASED RANGE, RADAR SENSITIVITY AND ANGLE ACCURACY****BACKGROUND**

5           The invention relates generally to radar, and more particularly, to radar systems having multiple antennas.

          In the field of radar systems technology, there continues to be a need for improved capability to handle potential lower cross section as well as longer range targets. In the past, this need has been met by developing larger, more sensitive (and thus more costly) radars.

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**SUMMARY**

          The present invention features a technique for combining multiple radars for increased sensitivity and range.

          In one aspect, therefore, a method of radar processing includes: radiating a first signal  
15   beam from an antenna of a first radar in the direction of a target; radiating a second signal beam from an antenna of a second radar in the direction of the target; receiving echo signals from the first signal beam at the first and second radars; receiving echo signals from the second signal beam at the first and second radars; processing the echo signals received at the first radar to  
20   produce first radar processed echo signals; processing the echo signals received at the second radar to produce second radar processed echo signals; and combining the first and second radar processed echo signals to form an aggregate value.

          Particular implementations of the invention may provide one or more of the following advantages. The present invention addresses a need for increased range and sensitivity to handle lower cross section and longer range targets as they appear in the future without having to build  
25   larger radars for them in the near term. The increased sensitivity is achieved by combining low

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sensitivity, lower cost radars with minor modification to achieve the higher sensitivity and increased range.

Other features and advantages of the invention will be apparent from the following detailed description and from the claims.

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### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a multi-radar combining system.

FIG. 2 is a conceptual depiction of the multi-radar combining system showing the paths of the transmit signal beams and corresponding echo signals for two radars.

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FIG. 3 is a block diagram of a portion of the system modified to combine coherently the echo signals for the same carrier frequency and combine the results (different carrier frequencies) using video integration.

FIG. 4 is a block diagram of an exemplary digital implementation of the multi-radar combining system.

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FIG. 5 is a table that shows sensitivity improvement for search and tracking modes based on different techniques of combining two radars.

Like reference numerals will be used to represent like elements.

### DETAILED DESCRIPTION

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Referring to FIG. 1, a multi-radar combining system 10 that combines radars to achieve enhanced capability, in particular, increased range and sensitivity, is shown. The system 10 includes multiple radars 12, shown in the illustrated embodiment as two radars 12a and 12b. Here radar 12b is the "master", although the roles could be reversed. The radars 12a and 12b each include a transmitter, shown as transmitter 14a and transmitter 14b, respectively. The

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outputs of the transmitters 14a and 14b are delivered to respective antennas 16a, 16b for radiation in the form of a transmit beam directed at a target (indicated by reference numeral 18). In the illustrated embodiment, the antennas 16a, 16b are rotating antennas; however, a stationary antenna could also be used. The antennas 16a, 16b collect echo signals received from the target, and the echo signals (which may be combined into monopulse receive signals) are processed by respective receivers 20a, 20b to detect the presence of the target and determine its location in range and in angle. In radar 12a, a duplexer 22a coupled to the transmitter 14a, receiver 20a and antenna 16a allows the antenna 16a to be used on a time-shared basis for both transmitting and receiving. A duplexer 22b, coupled to the transmitter 14b, receiver 20b and antenna 16b, provides the same functionality (as duplexer 22a) in radar 12b.

Still referring to FIG. 1, the receivers 20a and 20b include a low-noise amplifier ("LNA") 23a and a LNA 23b, respectively. The LNA 23a (of receiver 20a) is coupled to down converters 24a-1 and 24a-2, and the LNA 23b (of receiver 20b) is coupled to down converters 24b-1 and 24b-2. The down converters 24a-1, 24a-2, 24b-1 and 24b-2 (more generally, down converters 24) perform RF-to-IF conversion. Each of the receivers includes a receiver exciter ("REX"), a REX 25a in receiver 20a and a REX 25b in receiver 20b. The REX 25b of the master radar 12b (master REX) provides both transmit carrier frequencies  $f_1$  and  $f_2$ , with their modulations, and local oscillator signals  $LO_1$  and  $LO_2$  (indicated collectively by reference numeral 26), to radars 12a and 12b. In the example shown, with radar 12b serving as the master radar, REX 25a of radar 12a is in "by-pass" mode, that is, it does not operate as a REX but merely distributes within radar 12a the signals generated by REX 25b. In receiver 20a, the down converter 24a-1 and the down converter 24a-2 are connected to a signal processor 27a-1 and a signal processor 27a-2, respectively. In receiver 20b, the down converter 24b-1 and the down converter 24b-2 are

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connected to a signal processor 27b-1 and a signal processor 27b-2, respectively. The signal processors 27a-1, 27a-2, 27b-1 and 27b-2 (generally, signal processors 27) perform filtering, possibly including pulse compression filtering. The signal processors 27 are further connected to envelope detectors, more specifically, signal processor 27a-1 and signal processor 27a-2 are  
5 connected to envelope detector 28a-1 and envelope detector 28a-2, respectively, while signal processor 27b-1 and signal processor 27b-2 are connected to envelope detector 28b-1 and envelope detector 28b-2, respectively. The four envelope detected signals are added (video integrated) by a combiner 30 and passed to a threshold detector 32 for detection. The threshold detector 32 is coupled to and provides detection information to other conventional radar system  
10 elements, e.g., a tracker 34 and a display 36, as shown.

As indicated above, system 10 combines receive signals of radars 12a, 12b in a manner that achieves greater sensitivity gain and increased range. Referring now to FIG. 2 in conjunction with FIG. 1, the radars 12a, 12b to be combined are positioned in fairly close proximity to each other. The phase centers of the antenna 16a and the antenna 16b (in radar 12a  
15 and radar 12b, respectively), are spaced by a distance "D". The distance D is a flexible parameter. A small value for D may be selected to simplify the processing of the echo signals. If a larger distance is chosen, delays may be needed so that the echo signals can be added correctly (to within a fraction of a pulse width) during processing. Also, if coherent integration is used ( $f_1=f_2$ ), the effects of interferometric lobing become a concern when there is too much  
20 spacing between the radars. If the distance D is somewhat larger than the width "W" of the antenna 16, then a large interferometer baseline is formed when coherent combining on receive is used (as discussed shortly), with the result that the angle accuracy will be improved, in some cases by an order of magnitude.

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Referring again to FIG. 1, the rotation of the antennas of the multiple radars are synchronized by a synchronization signal provided by an azimuth servo 37b (in radar 12b) to an azimuth servo 37a (in radar 12a) so that the beams of the radars look in the same direction, to within a fraction of a beamwidth. The radars nominally radiate identical transmit signal beams (e.g., beams 40 and 42 for radars 12a and 12b, respectively) at the same time. The beams could, however, be different. The carrier frequencies  $f_1$  and  $f_2$  are different where incoherent transmit operation and incoherent receiver combining is used. The carrier frequencies  $f_1$  and  $f_2$  will be the same if coherent transmit operation and coherent receiver combining for all signals is desired, as discussed later. When the carrier frequencies  $f_1$  and  $f_2$  are different, they may differ sufficiently so that they do not interfere with each other and can be separated from each other in the radar receivers, yet are close enough to allow the same phase shift commands for a phased array antenna. Also, they may differ sufficiently to provide frequency diversity, i.e., the echo amplitudes are then independent at the two frequencies. In addition, the use of different carrier frequencies helps to avoid interferometric lobing, which is not desirable during search (and may not be desirable for tracking, either, if the radars are too far apart). The echoes of the transmitted signals from both radars are received by both radars.

FIG. 2 shows the path of the echo signals for both radars. Still referring to FIGS. 1 and 2, echoes from a transmit beam radiated by the antenna of radar 12a towards the target 18 are received at radar 12a, as indicated by reference numeral 50a (echo signals " $e_{11}$ "), and are received at radar 12b, as indicated by reference numeral 50b (echo signals " $e_{12}$ "). Similarly, the echoes of the transmitted signal from radar 12b are received at radar 12a, as indicated by reference numeral 52a (echo signals " $e_{21}$ "), and are received at radar 12b, as indicated by reference number 52b (echo signals " $e_{22}$ "). These four echoes 50a, 50b, 52a, 52b, are pulse



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compressed and pulse Doppler processed (if appropriate) in the appropriate signal processors 27 to produce processed echo signals  $s_{11}$  54a,  $s_{12}$  54b,  $s_{21}$  56a,  $s_{22}$  56b, respectively, as shown in FIG. 1. The four processed echoes are then envelope detected and video integrated to produce video integrated signals  $v_{11}$  57a,  $v_{12}$  57b,  $v_{21}$  58a and  $v_{22}$  58b, respectively. These four signals  
5 are combined to produce an aggregate value 59. It will be understood from the figure that the receiver of radar 12a handles the processing of signals  $e_{11}$  50a and  $e_{21}$  52a to produce  $v_{11}$  57a and  $v_{21}$  58a, respectively, while the receiver of radar 12b handles the processing of signals  $e_{12}$  50b and  $e_{22}$  52b to produce  $v_{12}$  57b and  $v_{22}$  58b, respectively.

In the embodiment illustrated in FIG. 1, the four echoes are combined incoherently in the  
10 radar receiver. Other techniques may be used to combine the echo signals as well. One example is shown in FIG. 3. Referring to FIG. 3, the combiner 30 of the receiver is suitably adapted to allow the processed signals having the same carrier frequency, e.g.,  $s_{11}$  and  $s_{12}$ , to be added coherently. Thus,  $s_{11}$  and  $s_{12}$  can be added coherently by a first adder 60a, and  $s_{21}$  and  $s_{22}$  can be added coherently by a second adder 60b. The resulting sum signals  $s_{11}+s_{12}$  (" $S_1$ ") and  $s_{21}+s_{22}$   
15 (" $S_2$ ") each are envelope detected by respective envelope detectors 62a, 62b. The envelope detected values  $v_1$  and  $v_2$  are combined by a third adder 60c to form the final, aggregate value 59.

Generally, for the search mode, it is found that coherent addition of the type described with reference to FIG. 3 does not provide any significant improvement in detectability over video integration (incoherent addition). This is the case because the phases of processed echo  
20 signals  $s_{11}$  and  $s_{12}$  (and  $s_{21}$  and  $s_{22}$ ) are not known, and so the signals have to be added with a bank of adders having different relative phase shifts, as will be described shortly. For the track mode, coherent addition can provide better SNR.

The processed echo signals may be combined using different techniques when the carrier

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frequencies  $f_1$  and  $f_2$  are equal as well. For example, the four processed echo signals may be combined coherently (track mode), or using a combination of coherent and incoherent integration (for track or search mode also). When  $f_1 = f_2$ , it is only necessary to have one mixer per radar. In the illustrated embodiment of FIG. 1, for the case of  $f_1 = f_2$ , only one pair of mixers, for example, 24a-1 and 24b-1 (or, alternatively, 24a-2 and 24b-2), need be used. As discussed later,  $f_1$  would be set equal to  $f_2$  generally for a track mode only.

The potential advantage of using coherent integration is that of providing improved sensitivity (about another 3 dB to about 9 dB) for the track mode. This improved sensitivity is realized because of the coherent addition that can result in beams from radars 12a and 12b at the target for  $f_1 = f_2$  when the signals from radars 12a and 12b are transmitted simultaneously. An interferometric pattern is produced on transmit. If the phase centers of the two radars are not known to a fraction of a wavelength, then more than one simultaneous transmission of the signals from radars 12a and 12b will be needed with different relative phase shifts between the signals for each transmission to ensure coherent addition at the target (or worded differently, to ensure that the target is near the peak of transmit interferometric peak). First a  $0^\circ$  relative phase shift would be tried. If the target is not detected (or the SNR is not as large as expected), then a  $180^\circ$  relative phase shift would be used. If the target is still not detected (or the SNR not large enough), a  $90^\circ$  relative phase shift could be used, followed finally by a  $270^\circ$  relative phase shift.

On receive, because the phases of the signals out of the radars 12a and 12b will not generally be known, the coherent combining will be performed using a bank of parallel channels each adding the two signals with a different relative phase shift. For example, eight phase shifts from  $0^\circ$  to  $315^\circ$  in steps of  $45^\circ$  could be used. After the best relative phase shift for receive was determined out of the eight possible phase shifts, the signals could be reprocessed with smaller

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phase steps to determine which gives the best SNR, so as to eventually achieve 9 dB improvement in SNR over that obtained with one radar in the track mode.

If the phase centers of the two radars were known to a fraction of a wavelength, it would not be necessary to use multiple transmissions with different phase shifts to get the signals from the two radars to add coherently at the target, i.e., to put a transmit interferometric lobe on the target. Instead, the phase shift needed to put a transmit and receive interferometric lobe on the target would be determined from knowledge of the location of the target to a fraction of a beamwidth. The target angle determination is obtained from the normal monopulse channel signals from the radars operated with  $f_1 \neq f_2$ . In this case, the standard monopulse outputs of radars 12a and 12b would be processed in the same way as described above (with reference to FIG. 3) for the sum signal outputs, but now to estimate the target angle. The coherent addition on transmit and receive can be further improved if defined by using the initial phase shifts for transmit and receive obtained from the monopulse measurements and then searching for better phase shifts for transmit and receive.

With  $f_1 = f_2$  it is possible to avoid having an interferometric pattern on transmit by transmitting the signals from radars 12 and 12b sequentially in time so as not to overlap in time on transmit or receive. The echo signals can then be added incoherently when appropriately delayed on receive. The sequential transmissions eliminate the need for two receivers in each radar. The improvement in sensitivity achieved with this technique is about 6 dB.

Once the target is detected, it is possible to estimate that target's azimuth (or elevation) angle very accurately. For  $f_1 \neq f_2$ , it is possible to determine the target's location in angle to a fraction of a receive interferometric lobe width. This determination can be made by measuring the phase of  $s_{11}$  relative to  $s_{12}$  and, likewise,  $s_{21}$  relative to  $s_{22}$ . Knowing these phases provides a

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very accurate estimate of the target angle, specifically to a fraction of a receive interferometric lobe width, which is much narrower than the width of the beams of each radar. The ambiguity as to which lobe the target is on is eliminated by using a normal monopulse measurement obtained with  $f_1 \neq f_2$  as described above.

5 For  $f_1 = f_2$ , the target angle is estimated accurately by measuring the phase between the signals out of receivers 22a and 22b independent of whether the signals are transmitted from radars 12a and 12b simultaneously or sequentially.

Other implementations of the radars 12a, 12b are possible. While the block diagram of FIG. 1 is intended to be conceptual in nature, it depicts an all analog implementation for the  
10 radars 12a, 12b. It will be understood, however, that the radar receiver can be designed for digital signal processing, as shown in FIG. 4.

Referring now to FIG. 4, the system 10 includes a digital signal processor 70 that receives echo signals from each of the down converters 24. In the exemplary digital processing implementation of FIG. 4, the signals correspond to in-phase ("I") and quadrature ("Q")  
15 channels. The digital signal processor 70 performs digitally those functions performed by units 27, 28 and 30 of system 10 as depicted in FIG. 1. The output of the digital signal processor 70, that is, the aggregate value, can be provided to threshold detector 32, as before.

Although the digital signal processor 70, like the units 27, 28 and 30, can be separate from the radars 12a, 12b, this circuitry could reside in one or both of the radars. If included in  
20 both radars, only the digital signal processor 70 in one radar operating as the master would be used during operation. The same can be said of the threshold detect 32, tracker 34 and display 36. In FIG. 4, as in FIG. 1, radar 12b is represented as the master. Any digital signal processing, threshold detect, tracking and display capability in radar 12a, to the extent that it may exist, has

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been omitted from the figure for simplification.

While only two radars are shown in the system examples of FIGS. 1 and 4, it will be appreciated that the multi-radar combining concept embodied therein can be extended to more than two radars. Also, although the radars 12a, 12b are described as rotating antennas, the  
5 technique described herein also applies to radars that use non-rotating phased arrays.

FIG. 5 shows a table that provides the Signal-to-Noise Ratio (SNR) sensitivity improvement (in dB) for different techniques of combining two radars. For a non-fluctuating target, the sensitivity gain of the combined radars (relative to a single radar) is approximately 6dB for searches regardless of whether coherent or incoherent integration is used (on transmit  
10 and/or receive). For track mode, when coherent integration is used on transmit and the frequency is the same for both radars (that is,  $f_1 = f_2$ ), the strength of the signal on the target is greater by 3 dB so that the SNR is now 3 dB higher for a total gain of 9 dB over that for a single target.

For the case of a fluctuating target (Swerling-II type), it is assumed that the two radars  
15 being combined as described above use carrier frequencies that differ sufficiently to provide frequency diversity. For a single look Pd of 90%, therefore, the resultant increase in sensitivity is 8.7 dB better than that of a single radar that does not use frequency diversity.

Other embodiments are within the scope of the following claims.

What is claimed is:

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1. A method of radar processing comprising:

radiating a first signal beam from an antenna of a first radar in the direction of a target;

radiating a second signal beam from an antenna of a second radar in the direction of

the target;

receiving echo signals from the first signal beam at the first and second radars;

receiving echo signals from the second signal beam at the first and second radars;

processing the echo signals received at the first radar to produce first radar processed echo signals;

processing the echo signals received at the second radar to produce second radar processed echo signals; and

combining the first and second radar processed echo signal values to form an aggregate value.

2. The method of claim 1 wherein the first and second signal beams have respective first and second carrier frequencies which are different.

3. The method of claim 2 wherein combining comprises combining incoherently all of the first and second radar processed echo signals.

4. The method of claim 2 wherein combining comprises:

combining coherently those of the first and second radar processed echo signals that have the first carrier frequency;

combining coherently those of the first and second radar processed echo signals that

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have the second carrier frequency; and

combining incoherently the results of the coherent combination for the first and second carrier frequencies.

5     5.     The method of claim 1 wherein the first and second signal beams have the same carrier frequency.

6.     The method of claim 5 wherein combining comprises:

combining coherently those of the first and second radar processed echo signals from  
10    the first signal beam to produce a first result;

combining coherently those of the first and second radar processed echo signals from the second signal beam to produce a second result; and

combining coherently the first and second results.

15    7.     The method of claim 5 wherein combining comprises:.

combining coherently those of the first and second radar processed echo signals from the first signal beam to produce a first result;

combining coherently those of the first and second radar processed echo signals from the second signal beam to produce a second result; and

20     combining incoherently the first and second results.

8.     The method of claim 5 wherein combining comprises:

combining incoherently those of the first and second radar processed echo signals from the first signal beam to produce a first result;

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combining incoherently those of the first and second radar processed echo signals  
from the second signal beam to produce a second result; and  
combining incoherently the first and second results.

- 5      9.      The method of claim 8 wherein the first and second signal beams are transmitted  
sequentially in time.
10.      The method of claim 1 wherein the antennas are synchronized rotating antennas.
- 10      11.      The method of claim 1 wherein the antennas comprise non-rotating phased arrays.
12.      A method of processing by a radar comprising:  
radiating a first signal beam in the direction of a target;  
receiving echo signals from the first signal beam;
- 15      receiving echo signals from a second signal beam radiated by a second radar in the  
direction of the target, the radar and the second radar being spaced a predetermined distance  
apart; and  
processing the echo signals from the first and second signal beams.
- 20      13.      The method of claim 11 further comprising:  
combining the processed echo signals with echo signals from the first and second  
signal beams that have been received by the second radar and processed, to form an  
aggregate value.
- 25      14.      A radar comprising:



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an antenna to radiate a first signal in the direction of a target;

a receiver to receive echo signals from the first signal beam and echo signals from a second signal beam radiated by a second antenna of a second radar in the direction of the target; and

5           circuitry to process the echo signals from the first and second signal beams, and to combine the processed echo signals with echo signals from the first and second signal beams that have been received by a receiver of the second radar and processed, to form an aggregate value.

10       15.    The radar of claim 14 wherein the circuitry comprises a digital signal processor.

16.    The radar of claim 14 wherein the circuitry comprises analog circuitry.

15       17.    The radar of claim 14 further including circuitry to synchronize rotation of the antenna with the second antenna of the second radar.

18.    The radar of claim 14 wherein the first and second signal beams have respective first and second carrier frequencies which are different.

20       19.    The radar of claim 18 wherein the circuitry combines the processed echo signals using incoherent integration.

20.    The radar of claim 18 wherein the circuitry combines the processed echo signals using both coherent and incoherent integration.

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21. The radar of claim 14 wherein the first and second signal beams have respective first and second carrier frequencies which are the same.

22. The radar of claim 21 where the circuitry combines the processed echo signals using  
5 coherent integration.

23. The radar of claim 21 wherein the circuitry combines the processed echo signals using incoherent integration.

10 24. The radar of claim 21 wherein the circuitry combines the processed echo signals using both coherent and incoherent integration.